

IMPROVED PROPORTIONAL-INTEGRAL (PI) LOGIC FOR CANAL AUTOMATION

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ABSTRACT: Successful implementation of Proportional-Integral (PI) control logic for gate automation on irrigation canals has been problematic because of difficulties in tuning the PI controllers for a wide range of flows. This research shows that successful and relatively simple tuning for upstream controllers can be accomplished if one uses the velocity form of the PI logic. The velocity form must be modified with a newly-developed Universal Factor (UF) concept, which accounts for the nonlinearity of the upstream water level response to gate movement. The UF function is unique for each check structure, and can be determined with a steady state simulation program. The technique was tested with unsteady flow simulations of a new control system for the Highline Canal in Grand Valley, Colo. Extreme flow rate changes were successfully controlled with minimal water level changes upstream of the check structures. Robustness of the Highline Canal control system was enhanced by incorporating the use of long weir walls into the radial gate structure design.

INTRODUCTION

Much work was done in the 1980s and early 1990s on developing new devices and algorithms for canal control. The work has been enhanced by the increasing availability of sophisticated desktop computer systems and the development of good open-channel, unsteady flow simulation programs (Rogers and Merkley 1993; Holly and Parrish 1993; Merkley and Rogers 1993; Clemmens et al. 1993; Schuurmans 1993).

Much of the theoretical canal control algorithm development work has focused on new concepts of downstream control or centralized control. However, the vast majority of irrigation canals still use upstream control (Burt and Plusquellet 1990). Interestingly enough, little effort has been spent on improving the relatively simple algorithms that are used to control automated upstream control gates that utilize Programmable Logic Controllers (PLCs). Two significant control problems remain: (1) Although it is relatively easy to tune controller constants for a single gate by trial and error procedures in a simulation program, it is extremely difficult to properly tune several gates which are in series; and (2) tuning constants that appear to work well at high flow rates often give poor performance at low flow rates.

Widespread availability, design advantages, and the relative low cost of reliable PLCs and Remote Terminal Units (RTUs) for irrigation canal control should provide an excellent opportunity to implement conventional industrial process control into irrigation canal control. Other industries have long used variations of the Proportional-Integral-Differential (PID) control technique.

Many books (Aström and Hägglund 1988; Mollenkamp 1984; Rogers et al. 1995) discuss the proportional, PI, and PID control methods in great detail. In practice, however, successful implementation in series on irrigation canals has been prob-

lematic. The Ziegler and Nichols classic techniques used to solve for the algorithm tuning constants do not work in canal systems with multiple gates, where high cross-coupling effects are present. The research results reported in this paper provide a revised PI algorithm with recommendations for a new technique to solve for controller tuning constants.

PROPORTIONAL-INTEGRAL (PI) CONTROL LOGIC

With proportional control, adjustment of the control structure is proportional to the deviation of the control variable (Liu 1995). Integral or reset action is often added to automatically adjust the reset of a proportional controller (Aström and Hägglund 1988). When both proportional and integral action are used, the logic is referred to as PI control. The derivative or derivative action is used when, in a slow process, action must be taken as soon as possible after an upset or else the time to recover will be too long (Mollenkamp 1984). Derivative action is not typically used in irrigation canal control algorithms.

The continuous-time PI controller is often written as follows:

$$u(t) = u + KP \times e(t) + KI \int_{\sigma=0}^t e(\sigma) d\sigma \quad (1)$$

where $u(t)$ = desired gate position at the present time, t ; u = gate position at the start time ($t = 0$), which is the proper gate position, manually set, to achieve the desired water level; $e(t)$ = error at any time, t ; σ = integration variable; t = present time; KP = proportional constant; and KI = integral constant.

For a digital implementation of the PI controller, in a computer or RTU, the integral part is approximated using the trapezoidal method (Isermann 1989). This gives

$$u(k) = u + KP \times e(k) + \tau \times KI \left[\left(\sum_{i=1}^{k-1} e(i) \right) + \frac{e(k) + e(0)}{2} \right] \quad (2)$$

where k = present time, and $k - 1$ is one time step prior; and τ = sampling time.

For gate control, these forms of the PI algorithm are problematic for two reasons:

1. One must have an accurate measurement of the gate position because the algorithm instructs the gate to move to a specific location (as opposed to requiring a specific amount of movement). Gate position indicators may have accuracy problems, and it is therefore preferable to request a change in gate position rather than to specify a gate position.

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2. One must know the initial value for the gate position at time zero. Different initial positions require different tuning constants.

PI CONTROLLER VELOCITY FORM

It is preferable to use the velocity or incremental form of the PI process control logic, because the two problems listed above are eliminated. The classical difference form of the PI logic is

$$\Delta u(k) = \left[\left(KP + \frac{\tau \times KI}{2} \right) \times e(k) \right] + \left[\left(-KP + \frac{\tau \times KI}{2} \right) \times e(k-1) \right] \quad (3)$$

where $\Delta u(k)$ = required change in gate position at time (k) , in feet; $e(k)$ = error at time (k) , in feet (i.e., actual water level minus setpoint level); $e(k-1)$ = error at the previous time step, $(k-1)$, in feet; KP = proportional constant; KI = integral constant; and τ = sampling time, in minutes ($\tau = 1$ for 1 minute).

A problem with all PI equations that have been proposed for canal control (whether for upstream or downstream control) is that they assume the required movement of the gate in response to an upstream water level disturbance is the same, regardless of the gate position. This, however, is not the case. The required gate response is actually nonlinear with respect to gate position.

The result is that it is very difficult to tune the controller constants (KP and KI) of any standard PI forms (including the velocity form) for each individual gate in a canal. Each gate in a canal has a different gate/pool geometry and interaction. Proper tuning for a rapid and stable canal response requires that all gates in a canal be simulated and tuned together, because potential controller instabilities rarely show up if one gate is tuned by itself. Because each gate is different, and requires a different set of controller constants, satisfactory simultaneous and unique tuning of each gate is almost impossible to accomplish.

CONCEPT OF UNIVERSAL FACTOR, UF

To simplify tuning of the control constants, and to make the gate algorithm applicable to a more general situation involving several different kinds of gates in a single canal, the concept of UF was added to the difference form of the PI equation such that

$$\Delta u(k) = UF \times STP \times \left\{ \left[\left(KP + \frac{\tau \times KI}{2} \right) \times e(k) \right] + \left[\left(-KP + \frac{\tau \times KI}{2} \right) \times e(k-1) \right] \right\} \quad (4)$$

where UF = relative change in gate opening required to compensate for a 0.03-m (0.1-ft) change in the upstream water level, assuming that the gate did not move when the water level changed (The value of UF depends upon the gate position); STP = upstream set point water depth (target level). This is a constant value, as opposed to the constantly changing upstream water level.

The UF function is unique for each gate; it depends upon the interaction between the canal configuration and the gate design. The UF function produces an amount of gate movement that is just sufficient to offset the flow rate change associated with a change in water level, regardless of the initial gate opening. The UF factor effectively calibrates the gate so this occurs, which has additional implication for flow control strategies.

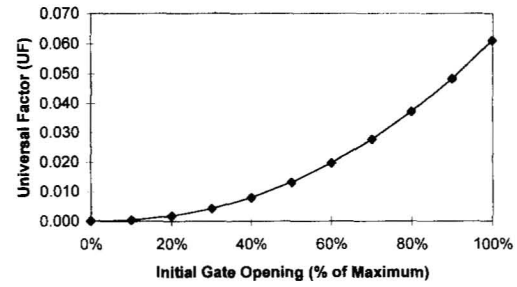


FIG. 1. Relationship between UF and Initial Gate Opening as Percent of Maximum

The general form of the UF equation is

$$UF = f(U) = a(X)^b \quad (5)$$

where U = gate opening; UF = Universal Factor described earlier; X = relative gate opening at that time

$$X = \frac{\text{gate opening}}{\text{upstream setpoint water depth}} = \frac{U}{STP} \quad (6)$$

and a and b are constants related to the particular canal/gate configuration.

This equation form was found to provide an excellent description ($r^2 > 0.90$) for UF , based on computer simulation studies with canals having a wide range of shapes, velocities, gate sizes, etc. Because of the good numerical fit, later work only used two points to estimate the UF equation. Fig. 1 shows the smoothed relationship between UF and the initial gate opening as a percent of maximum opening for 7.3-m- (24-ft-) wide gates in a six-pool canal of 6,096 m (20,000 ft) length, 6.1 m (20 ft) depth and with a trapezoidal cross section.

DETERMINATION OF a AND b FOR UF

The constants a and b are determined using an unsteady flow computer simulation model, although a steady state model would be sufficient. In this case, CanalCAD was used. CanalCAD has been developed over the past six years with funding from Imperial Irrigation District, Imperial, Calif.; the U.S. Water Conservation Lab, Phoenix, Ariz.; the U.S. Bureau of Reclamation, Denver, Colo.; and the Irrigation Training and Research Center, San Luis Obispo, Calif. (Holly and Parrish 1992).

The steps followed in the characterization procedure are summarized as follows:

1. Modify the canal model placing the gates to be automated under "idealized upstream control" using the desired upstream setpoint. In CanalCAD, idealized upstream control is designed to perfectly impose an upstream water level regardless of changes in the flow rate (Holly and Parrish 1992).
2. Decide which gate to characterize first and run a steady state simulation at some low flow rate. Preferably, the rate will result in an initial relative gate opening of about 0.20 (i.e., the gate is 20% of the distance between complete closure and the upstream water surface). Record the resulting gate opening.
3. Using the same canal layout, reclassify the first gate, which is to be characterized as a "manual underflow gate." The scheduled gate opening is set to the value observed in step 2.
4. Run another steady state simulation using the flow rate from step 2. Record the water level value observed immediately upstream of the manual gate, which should be very close to the set point value used with the automatic gate.

5. Increase the incoming (headworks) canal flow rate slightly until a steady state simulation at the same gate opening produces an upstream water level that is 0.03 m (0.1 ft) above the initial level observed in step 4.
6. Using the flow rate determined in step 5, run another steady state simulation. This time the control file containing the automatic gate is used. Note the new gate opening required to maintain the desired upstream setpoint.
7. The difference between the gate opening in step 6 and the one observed in step 2 is the change in gate opening required to compensate for a 0.03 m (0.1 ft) increase in upstream water level. Dividing by the upstream water depth produces a value for UF for this relative gate opening.
8. Repeat steps 1–7 using a higher initial flow rate (one that will result in an initial relative gate opening of about 0.50—i.e., 50% of STP).

To find the relative change in gate opening in each case, the change in gate opening is divided by the upstream water level set point. To calculate the constant b , the following equation is used:

$$b = \frac{\log(UF_1/UF_2)}{\log(X_1/X_2)} \quad (7)$$

where b = unknown constant for this gate; UF_1 and UF_2 are relative changes in gate openings for the two initial flow rates

$$X_1 = \frac{U_i}{H_{ws}} \quad (8)$$

$$UF_1 = \frac{\Delta U_i}{H_{ws}} \quad (9)$$

U_i = initial gate opening; H_{ws} = upstream water depth; ΔU_i = change in gate opening; and X_1 and X_2 are the initial relative gate openings at the two initial flow rates. The unknown constant a is found by

$$a = \frac{UF_1}{X_1^b} \quad (10)$$

These steps are repeated for each check structure to be characterized. Each time, the check structure of interest should be modeled as accurately as possible, while simultaneously simulating the other checks as ideal upstream water level controllers so that they provide the proper backwater influence on the structure of interest. Different a and b constants will be obtained for each location.

DETERMINATION OF KP AND KI VALUES

Successful determination of optimum gate control PI tuning constants (KP and KI) requires repetitive simulations with an excellent unsteady flow computer simulation program. The procedure within CanalCAD is as follows:

1. Using CanalCAD, each gate to be automated should be entered as a user-defined "FORTRAN automatic gate."
2. Enter some initial values for KP and KI. The same KP and KI constants should be used for all gates.
3. Enter the a and b values previously determined for each gate. These numbers are different for each gate and will not be changed during the tuning procedure.
4. Develop a schedule of flow rate changes that will tend to cause the gates to move throughout their full range of motion.
5. Perform a transient (all calculations) simulation.
6. Observe the water levels immediately upstream of each gate. If the choice of KP and KI is a good one, the upstream water level should remain steady throughout the simulation. A simulator with graphical output is very helpful for this step.
7. Information should be recorded using a grid with KP and KI values on the horizontal and vertical axes. For each combination of KP and KI, one should list a qualitative assessment of the gate control results.
8. Increment either KP or KI and run another simulation. Continue this process until the optimum values for KP and KI have been determined. The optimum values will produce the most stable water levels with the least amount of gate movement.

IMPORTANT ALGORITHM CONSTRAINTS

The value for X (the relative gate opening) must be limited to a minimum value of 0.30 in the equation used to compute UF. If this is not done, at a small initial opening the gate will respond too slowly to a sudden change in canal flow rate.

A second point is that the gate movement must be limited so that the gate is always submerged in the upstream water level by at least 0.03 m (0.1 ft). This prevents the flow regime from changing from an orifice to a weir condition. With the gate always in the water, better control is also achieved than if the gate is allowed to rise above the water surface, requiring time to return to a control condition.

Third, the gate movements within the simulation program (CanalCAD) must be of a realistic magnitude (such as a minimum of 3 cm), which will match hardware constraints in the field.

HIGHLINE CANAL

An improved PI logic, developed with these techniques, will be used to automate a series of gates on the Highline Canal in Grand Valley, Colo. The canal was constructed by the U.S. Bureau of Reclamation, and is currently operated by the Grand Valley Water Users Association.

Prior to the simulation work, detailed field work was performed to verify gate dimensions, roughness, and canal pool geometries. Water levels in the canal were also obtained at 15 locations with three flow rates per location. Those results were then used to calibrate CanalCAD. Calibration was almost exclusively done by slightly modifying roughness values and adjusting bottom widths in locations where differences occurred between the simulated water levels and actual field-recorded water levels.

Six new automatic upstream control structures have been proposed on this canal. In addition, one existing structure will be automated. The proposed gate structure design consists of a centered pair of 3.6-m- (12-ft-) wide radial gates with long-crested weir wing walls extending off the sides. This design, though unusual, was chosen to enhance the robustness of the system in the event of power or mechanical failures.

Determination of UF for Each Gate

The UF for each gate was determined using the procedure outlined previously. Table 1 summarizes both the constants obtained for the radial gates and the UFs used in the PI algorithm. Although the gates are identical in each structure, the upstream setpoint varies, and the downstream water levels are not identical for each structure. This explains the different UFs needed.

TABLE 1. Summary of *a* and *b* Gate Characterization Constants, Highline Canal

Gate (1)	<i>a</i> (2)	<i>b</i> (3)	UF (4)
Lewis wash	0.137	0.746	$0.138 \times U_i^{0.747}$
Gate A1-1/4	0.216	1.079	$0.216 \times U_i^{1.079}$
Gate A7	0.153	0.976	$0.153 \times U_i^{0.976}$
Gate A15	0.176	1.037	$0.176 \times U_i^{1.038}$
Gate A21.5	0.220	1.060	$0.221 \times U_i^{1.060}$
Gate A27	0.191	1.086	$0.192 \times U_i^{1.087}$
Gate A32	0.333	1.360	$0.334 \times U_i^{1.361}$

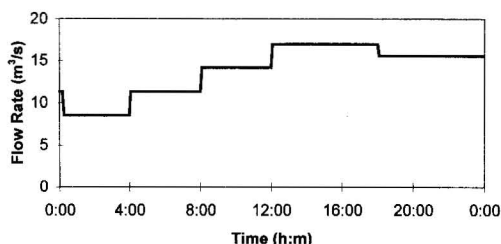


FIG. 2. Highline Canal Head Flow Rate versus Time

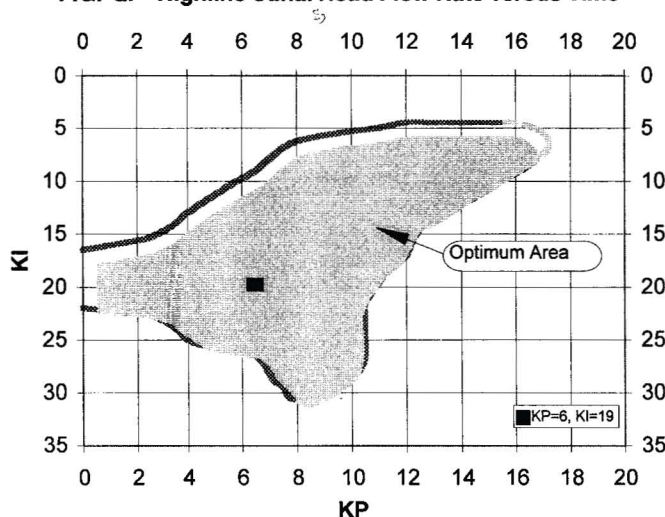


FIG. 3. Selection Grid Used to Isolate Optimal Values for KP and KI on Highline Canal Project

Determination of KP and KI Values for Highline Canal

To properly evaluate the ability of the automatic gate control algorithm to maintain a constant upstream water level, 24-h simulations were run. The flow rate schedule turned into the head of the canal is shown graphically in Fig. 2.

A large number of simulations were run to accurately define the envelope of acceptable KP/KI values. Fig. 3 is an abbreviated version of the KP/KI grid produced for this project. The range of acceptable KP/KI constants is clearly not symmetrical. Also, for KI values between approximately 15 and 22, there appeared to be no minimum value for KP. While the range of KP and KI values is not particularly large, each pair of constants satisfies all seven proposed new gates in the canal.

To allow the greatest degree of variation between the CanalCAD simulations and actual conditions in the field, the KP/KI combination at the centroid of this irregular envelope of acceptable values was selected. The recommended values for KP and KI were therefore determined to be 6 and 19, respectively.

Quality of Control Achieved

Fig. 4 shows upstream water levels versus time for the simulated, automated gates in the Highline Canal using KP and KI constants of 6 and 19, respectively.

Excellent control of upstream water levels was obtained when appropriate KP and KI values were used. At all times during the simulation, water depth was maintained to within 0.02 m (0.05 ft) of the target level even though the flow rate changes were extreme.

Amount of Gate Movement

Fig. 5 shows the gate positions versus time for each of the proposed new check structures on the Highline Canal. Data for this chart were produced by CanalCAD using the recommended KP/KI values of 6 and 19.

The largest magnitude gate movement was 6.5 cm/min (0.21 ft/min). This only occurred one time during the 24-h simulation. The vast majority of gate movement occurred at speeds less than 4 cm/min (0.13 ft/min). The control algorithm used in the simulator restricted gate movements to a minimum of 3 cm/min. Fig. 6 shows the frequency of the combined gate movements for all seven new gates in the canal using the flow rate changes described earlier. For the seven gates combined, there were a total of 385 gate movements in the 24-h simulation, averaging 55 movements per gate.

Considering the large magnitude of flow rate change, 55 gate movements in 24 h is very small. One key factor for excellent water level control and minimal gate movement is

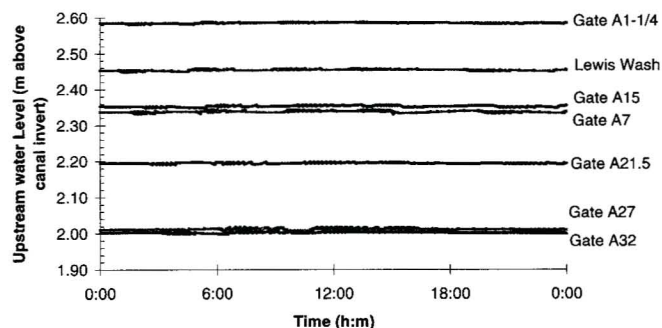


FIG. 4. Simulated Upstream Water Levels versus Time, Highline Canal (KP = 6; KI = 19)

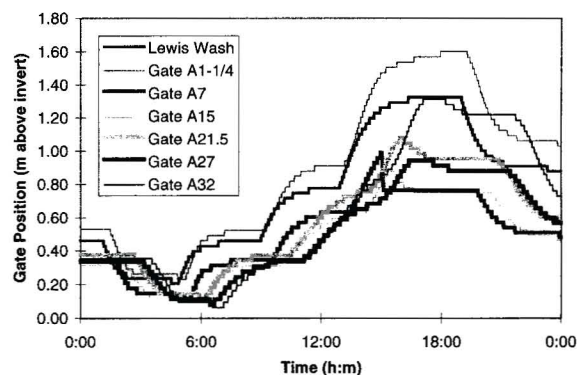


FIG. 5. Simulated Gate Positions versus Time for Proposed Gates on Highline Canal (KP = 6; KI = 19)

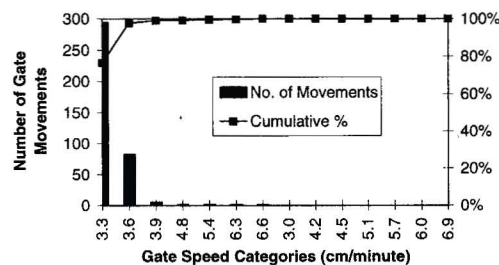


FIG. 6. Histogram of Combined Gate Movements for Seven Proposed Gates on Highline Canal (KP = 6; KI = 19)

the fact that long weir walls are used in addition to the automated radial gates. The long-crested weirs help to minimize gate movement and also dampen the magnitude of sudden rises or falls in water levels.

CONCLUSIONS

This research shows that successful tuning over widely varying flowrates can occur if one uses the difference form of the PI logic, along with a newly developed UF concept that accounts for the nonlinearity of the relationship between the upstream water level and gate movement. The technique was tested with simulations of a new control system for the High-line Canal in Grand Valley, Colo. Robustness of the control system was enhanced by incorporating the use of long weir walls into the radial gate structure design.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

- a = UF constant related to canal gate configuration;
- b = UF constant related to canal gate configuration;
- $e(k)$ = error at any time, $k(L)$;
- $e(k - 1)$ = error at the previous time step (L);
- $e(t)$ = error at any time, $t(L)$;
- H_{us} = upstream water depth (L);
- KI = integral constant of a PI algorithm;
- KP = proportional constant of a PI algorithm;
- k = present time (T);
- STP = upstream water level setpoint (L);
- σ = integration variable (T);
- t = present time (T);
- u = gate position at the start time ($h = 0$)(L);
- $u(t)$ = desired gate position at the present time, $t(L)$;
- UF = Universal Factor;
- U_i = initial gate opening, (L);
- X = gate opening relative to the upstream water level setpoint;
- Y = relative change in gate opening;
- $\Delta U(k)$ = required change in gate position at time, $k(L)$;
- ΔU_i = change in gate opening (L); and
- τ = sampling time in minutes (T).